LCA Methodology

Proposal of a Method for Allocation in Building-Related Environmental LCA Based on Economic Parameters

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Abstract. Application and development of the LCA methodology to the context of the building sector makes several building specific considerations necessary, as some key characteristics of products in the building sector differ considerably from those of other industrial sectors. The largest difference is that the service life of a building can stretch over centuries, rather than decades or years as seen for consumer products. The result of the long service life is that it is difficult to obtain accurate data and to make relevant assumptions about future conditions regarding, for example, recycling. These problems have implications on the issue of allocation in the building sector, in the way that several allocation procedures ascribe environmental loads to users of recycled or reused products and materials in the future which are unknown today. The long service life for buildings, building materials and building components, is associated with the introduced concept of a virtual parallel time perspective proposed here, which basically substitutes historical and future processes and values with current data. Further, the production and refining of raw material as a parallel to upgrading of recycled material, normally contains several intermediate products. A suggestion is given for how to determine the comparability of intermediate materials.

The suggested method for allocation presented is based on three basic assumptions: (1) If environmental loads are to be allocated to a succeeding product life cycle, the studied actual life cycle has to take responsibility for upgrading of the residual material into secondary resources. (2) Material characteristics and design of products are important factors to estimate the recyclable amount of the material. Therefore, a design factor is suggested using information for inherent material properties combined with information of the product context at the building level. (3) The quality reduction between the materials in two following product life cycles is indicated as the ratio between the market value for the material in the products.

The presented method can be a good alternative for handling the problem of open-loop recycling allocation in the context of the building sector if a consensus for the use of the fictive parallel time perspective and the use of the design factor can be established. This as the use of the time perspective and design factor is crucial to be able to deal with the problem of long service lives for buildings and building materials and the specific characteristics of the same building materials and components built into different building contexts.

Keywords: Allocation; building materials; economic value; LCA; Life Cycle Assessment (LCA); material quality; open-loop recycling; recyclability

Introduction

Allocation in LCA according to ISO 14040 is defined as: 'Partitioning the input or output flows of a unit process to the product system under focus' (ISO 1997). The process of partitioning input or output flows of a unit process is conducted by applying an allocation procedure. This definition concerns allocation in case of multi functional processes, where the input or output flows of the unit process are to be distributed between the products generated by that process. The products (co-products) in the case of multi functional processes are usually produced simultaneously or successively but with in a short period of time, e.g. electricity and heat generation in a combined energy plant (Frischknecht 2000).

In case of allocation over recycling or reuse cascades, where the material undergoes a change in the inherent properties (open-loop recycling), the allocation will not take place in the context of simultaneously produced products, but rather distributes environmental loads between succeeding life cycles. Open-loop recycling, however, can be regarded as a special case of multi functional processes and is regarded as such in ISO 14041 (ISO 1998), which also states that a stepwise allocation procedure shall be applied.

The outline of the procedure in ISO states that the first option to consider is to either divide the unit process or to expand the studied system and by that be able to avoid allocation. First if it is not possible or feasible to avoid allocation, then the inputs and outputs should be distributed based on physical relationships between products. As a third alternative, when the two former steps are not applicable, there is a possibility to use other relationships as a basis for allocation. An example of such other relationships is economic value. Regarding open-loop recycling as a special case of multi functional processes, ISO 14041 has stated that the same principles and procedures are applicable in the case of recycling as for multifunctional processes. The standard, however, has several additions that clarify the ISO view on open-loop allocation procedures. Examples of these clarifications are that '*changes in the inherent properties of materials shall be taken into account*' and that allocation procedures should use physical properties, economic value

or the number of subsequent uses of the recycled material as the basis for allocation (ISO 1998).

Even though an allocation in the case of multifunctional processes and recycling is usually presented as being an allocation within two different systems, this is often not the case. It is instead common that the systems subjected to an LCA study consist of unit processes that are multifunctional processes, recycling processes or both multifunctional and recycling processes at the same time (Frischknecht 1998).

There is today a vast number of procedures/methods for open-loop recycling allocation available that are based on a number of different approaches, e.g. quality reduction approaches proposed by Hauschild and Wenzel (1998) and Karlsson (1998), economic approaches proposed by Huppes (1994) and Frischknecht (1998), or arbitrary systems.

The choice of allocation procedure can have a large influence on the result of an LCA, which has been shown in two earlier studies by two of the authors, (Trinius and Borg 1998:1) or (Trinius and Borg 1998:2), and in other studies by e.g. Lindfors et al. (1995). This large influence on LCA results emphasises the importance of a consciously chosen approach, i.e. the choice of allocation procedure must be in compliance with the goal of the study, reflect the characteristics of the studied system and the decision situation (the context of the allocation).

From the stipulated goal of the study, the mode of assessment, either retrospective or prospective (Weidema, 1998), is determined. A retrospective study is a study of an existing system without an analysis of the effects of a choice or action, e.g. environmental reports and declarations, a type 0 study according to Frischknecht (Frischknecht 1997). A prospective analysis on the other hand is a change-oriented analysis, e.g. system optimisation and product development, a type 1-3 study depending on the time perspective, i.e. from short to long-term change-oriented studies (Frischknecht 1997). Ekvall (1999) has presented a proposal of a method based on market flexibility to be able to include the changes in the market situation caused by an alteration of systems.

Examples of characteristics of a system that are of importance are the degree of impact that the system has on adjacent systems, e.g. a recycling system's influence on the total amount of recycled material, the recyclability and reusability of the produced materials, products or services produced, and material quality.

The context of the allocation, i.e. the decision situation, and the parties involved and effected by the allocation, has to be identified. In cascade systems, which are the main focus of this article, two or many decision-makers are usually involved in establishing an acceptable allocation procedure (Frischknecht 1998). A single decision-maker is also possible as the receiving system of a recyclable or cascade material used, e.g. in a building application today, is not identifiable due to the very long time perspective.

1 Building-Specific Considerations

Applying and developing the LCA methodology to the context of the building sector makes several building-specific considerations necessary. These considerations originate in the fact that some characteristics of products in the building sector differ considerably from those of other industrial sectors. The largest difference is that the service life of a building can stretch over centuries rather than decades or years, as for other industrial products' service lives. The long service life of buildings has as a consequence that it is difficult to obtain accurate data and to make relevant assumptions about future conditions regarding recycling. These problems have implications on the issue of allocation in the building sector in the way that several allocation procedures ascribe environmental loads to users of recycled or reused products and materials in the future, which are unknown today.

Another aspect to be addressed is the definition of the product, and consequently the functional unit to be addressed by the assessment. Four different system levels can be identified regarding building-related environmental assessments (Paulsen 1999), stretching from low system levels (low complexity), such as materials and resources via building materials and components, to high system levels (high complexity consisting of entire buildings), see Fig. 1. The system level on which the product is addressed has considerable influence on where the system boundaries are to be set. Further, the problem of open-loop recycling allocation varies with the system level.

As open-loop allocation is carried out in the case of recycling or reuse, the item that is going to be recycled or reused has to be identified. In the case of the recycling of materials, products and components, the recycling always concerns material included in products and components. However, the recyclability of a product is not only dependent on the characteristics of the materials included, but also on the context that the product is built into and the design of the product. Whereas recycling only concern materials, products on higher system levels like building materials, components or entire buildings can be reused, i.e. detached from their old context, and be reapplied in a second use.

The consequences of this reasoning are to be found in the identification of the environmental loads that are to be included in an allocation procedure. As recycling is performed on the building material level and higher levels, the environmental loads associated with the actual production of the product are not to be included in the open-loop recycling allocation, but those efforts and processes that deliver the material as such are to be included. Facing reuse on the other hand, where the entire product or component is taken into a second use, all environmental loads generated during the manufacture of the material and the product are to be included in the allocation.

Use-related environmental loads are never to be included in allocated loads, as evidently the succeeding product's environmental performance is not reasonably to be influenced by the use characteristics of the preceding use. The topic of reuse, however, will not be elaborated further in this article.

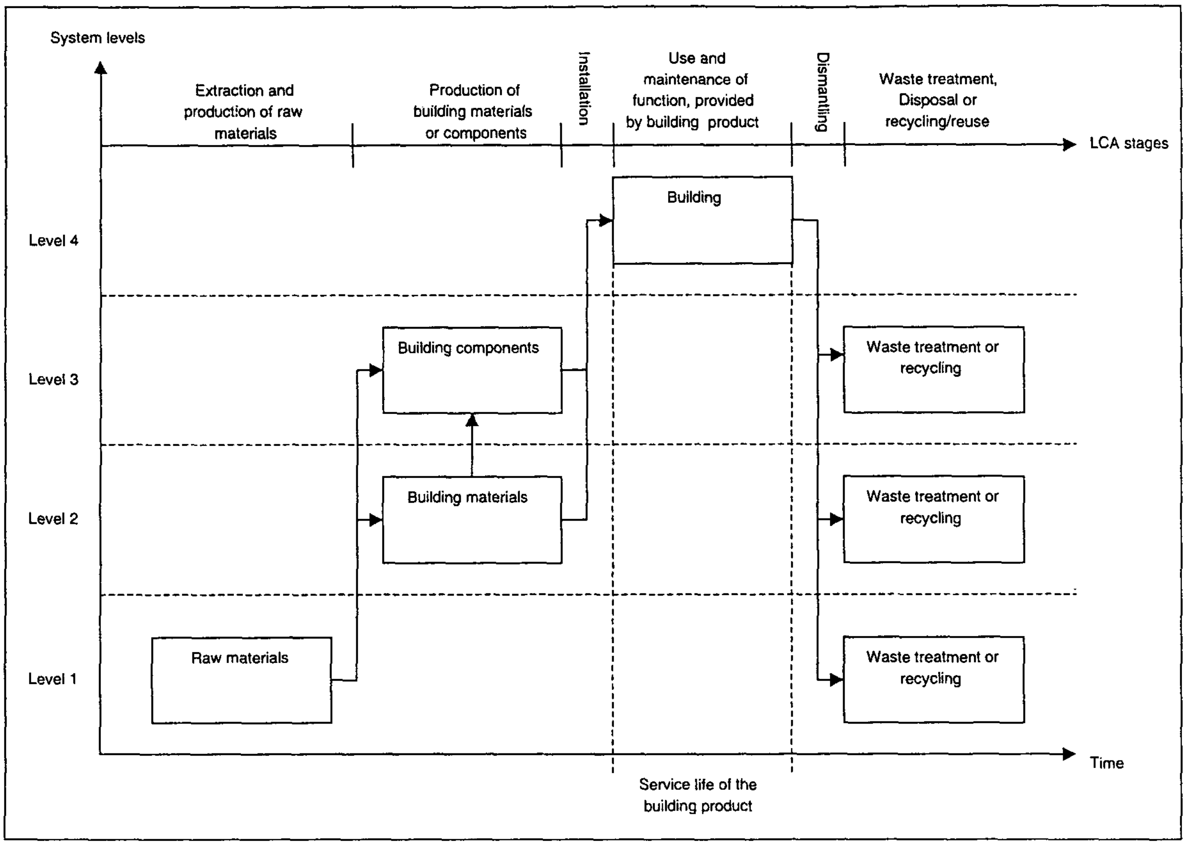

Fig. 1: System levels in a building product life cycle (Paulsen 1999)

2 Allocation and Recycling in the Building Sector

In general, allocation in the case of recycling of products has to solve two basic questions in order to enable an identification of the environmental loads that are to be associated with and allocated to the actual product:

- Which environmental loads from primary material production can be passed along after the use phase of the product? and
- Which environmental loads are inherited from preceding utilisations of the material incorporated in the actual product?

The environmental loads assigned to the actual product then consist of the loads *inherited* from preceding utilisations, *caused* during the life cycle of the actual product, and a possible reduction based on the amount of environmental loads that can be *passed along* to succeeding utilisations. From the discussion in this article, it will become clear, that there are numerous issues to be addressed when developing a method for allocation for this application context. The starting point may be said to be the simple equation where the

Allocated environmental load = inherited load + caused load – forwarded load

An identification of the inherited load and the forwarded load has to include the determination of reasonable allocation factors, as well as the identification of environmental loads that are to be included in the allocation. Hence, the discussion in this article includes aspects of system levels, intermediate materials, quality reduction, economic values, and design factors that all serve their part in the process of identifying reasonable shares of environmental loads that can be or are to be allocated.

In the following, an approach is presented that is an attempt to develop a method for allocation that is acceptable, applicable and feasible for use in the building sector. The proposed method is based on a combination of the parameter economic value of materials in different stages of their life cycle as an indicator of material quality and usefulness and design factor. The design factor is a parameter indicating the probable recyclability of the building material based on material characteristics in combination with the context the material is built into.

Focus is on virgin material in products recycled into secondary material in a following product. Further, an attempt is made to split the production processes of virgin and secondary materials into two parallel production processes. This is done to make it possible to compare the two material upgrading systems (virgin and recycled materials). Both systems can enclose several intermediate materials with different qualities, market values and aggregated environmental loads. To promote the acceptability, and fairness of an allocation approach based on economic values, it seems important, that a comparison of primary and secondary material is carried out for materials on an equivalent level in the

upgrading system. Especially for secondary raw material, market values occur on different material levels. One key issue is to detect which 'useful values' from the primary production system are to be transferred forward to the secondary product system.

3 Proposal of an Allocation Method for Recycling Based upon Economic Value of Materials

Determination of allocation factors

The procedure of determining allocation factors consists of the following steps:

- Positioning in the production chain (3.1)
- Determination of the environmental loads to be allocated (3.2)
- Determination of a design-dependent recyclability factor (3.3)
- Estimation of the economic value of the relevant products of comparison (3.4)

3.1 Positioning in the production chain

In Fig. 2, a simplified flow chart illustrates how a virgin raw material is used in a product followed by recycling of the material into a material pool for recycled material. The dotted line symbolises where the virgin raw material (V) leaves the life cycle of the primary product (P1). The recovery and upgrading process is divided into two parts to show that maybe not all of the material is recycled. Fraction WF in Fig. 2 is that part which is assumed to leave the system as waste, and it is therefore ascribed to the primary product P1. The recyclable part is named RF in Fig. 2 (RF+WF=1). The production of virgin material and the recycling processes are highlighted because they can be allocated between the primary product and the following product using recovered material R. The suggested method for allocation presented in the following is based on three principles:

1) To allocate environmental loads from raw material production forward to a succeeding product life cycle, the proceeding lifecycle has to take responsibility for the upgrading of the recycled material to a clearly defined and relevant level (see Fig. 3).
2) Only loads from the part that can be expected to be recycled shall be allocated forwards. Material characteristics and design of products can be important factors to estimate the ratio between the waste fraction (WF) and the recycled fraction (RF).
3) The quality reduction between the materials in two subsequent product life cycles is indicated by the ratio between the market value for the material in the products.

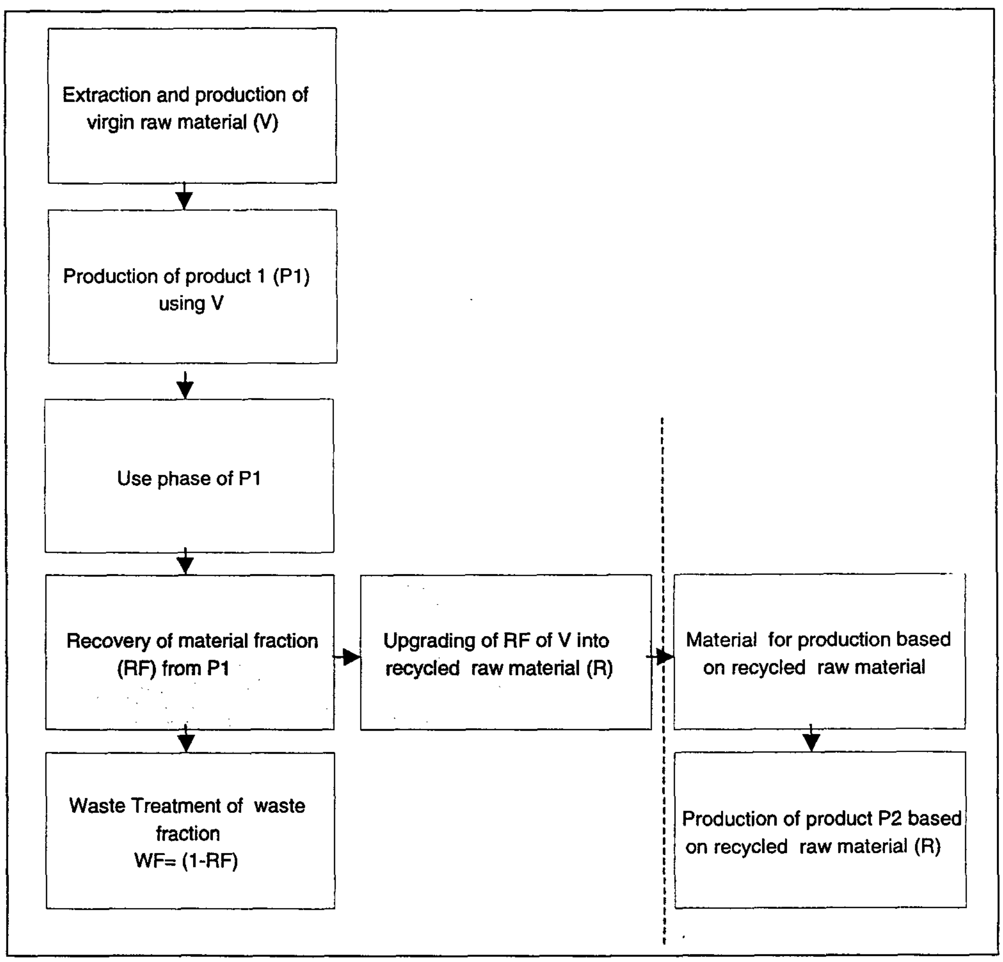

Fig. 2: Determination of processes for allocation between primary and secondary products

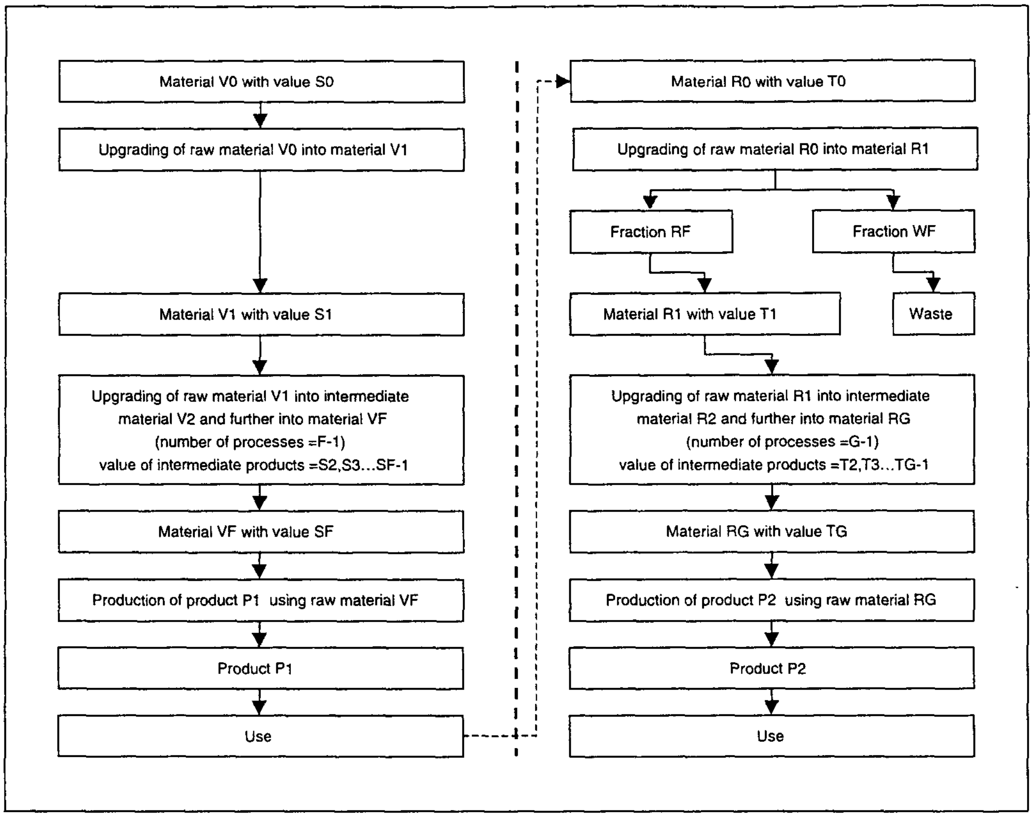

Fig. 3: Production processes for virgin and recycled material

Principles 1 and 2 have earlier been motivated in (Hauschild and Wenzel 1998). The use of economic values as a basis for allocation (principle 3) is suggested in ISO 14041 (1998). Further, an example is given in (Werner and Richter 2000), although there is no sharp distinction between material loses and quality loses in the later article.

In the suggested method for allocation based on economic residue values, a crucial issue is to find the environmental loads for the primary and secondary material production. Further, the market value for the materials in both product cycles has to be found.

Regarding the first of the three allocation principles described above, a further analysis of the virgin and recycling process for the production of raw materials is needed. As shown in **Fig.** 3, economic values and environmental loads occur in different steps for the two parallel material productions.

As shown in Fig. 3, a raw material (V0) is extracted and upgraded to a final material (VF) ready for the production of product P1. During the upgrading processes, several intermediate products can occur with different values and aggregated loads. The index 'F' is the number of the final product in the virgin raw material production chain. V0 symbolises the unextracted raw material. The first step in the raw material production is to extract the material to produce the first intermediate product V1 with the market value S1. Characteristic for V1 is that it can be regarded as available for the technical system. The intermediate product V1 can in some cases be directly ready for product production (P1), and thereby the parameter F=1 and V1=VF. However, production and refining of raw materials normally contains several processes and intermediate products. Between V1 and VF, an intermediate product can be identified as Vn where n = 2,3...F-1, with the market value being Sn and aggregated loads being $L_{V0\rightarrow Vn}$. Material VF is used to produce the primary product P1, which is then applied into a function (building). The bold dotted line symbolises the time gap between the beginning and end of service life for product P1.

At the end of P1's service life, while still remaining in the building, R0 is the material potentially available for recycling. Characteristic for R0 is that it is not available for further production, before it has been 'extracted' from the building. The upgrading process from R0 into R1 is dismantling and sorting into the recycled fraction (RF) and a final waste fraction (WF). Material R1 needs to be upgraded to material RG to produce product P2. Similar to the virgin production, the index 'G' is the number of the final product in the secondary raw material production chain. The recycling process can also contain several processes and intermediate products. Between R1 and RG, an intermediate product can be identified as Rm where m = 2,3...G-1, and with the market value Tm and aggregated loads $L_{R0\rightarrow Rm}$.

A comparison can be done between the two parallel processes. Material RG can be seen as equal to material VF in the aspect that both materials are available and ready to use for a product production, even though they do not necessarily have the same quality. Product R0 can be compared to

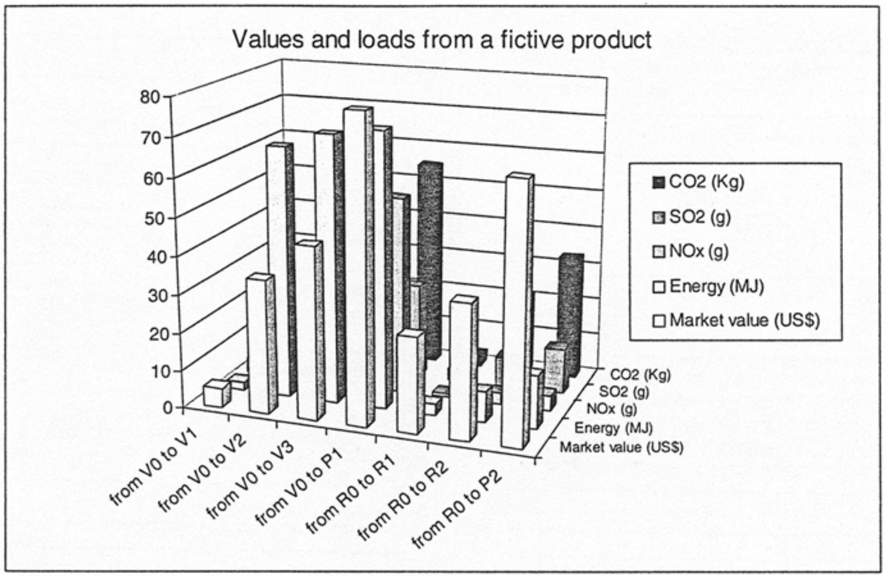

Fig. 4: Illustration of market value and aggregated environmental load vector for different material levels

product V0 in the aspect that both materials are unextracted, and R1 to V1 because both materials are available for further upgrading. However, both R0 and R1 can in some cases be gained from upgrading processes for V2 and onwards. For the intermediate products, it is desirable to identify comparable materials expressed as Vn and Rm.

The environmental loads from each process can be comprehended as a vector representing several load parameters as CO_2, NO_X, etc., this is illustrated in **Fig. 4**. A fictive scenario is chosen with two intermediate products for material V (F=3) and one intermediate product for material R (G=2).

As illustrated, the loads are aggregate from V0 to P1 and from R0 to P2. The market value can also be seen as an aggregated value in the form of a gradual increase in cost and benefits for each process. However, the market value is set by the market, independent of the relation between benefits and costs, whereas the environmental loads depend on each process. The notation $L_{V0 \rightarrow V2}$ is used for the aggregated environmental load from transforming material V0 into V2.

3.2 Determination of the environmental loads to be allocated

As described above, the production of virgin materials and the recycling processes can be divided into several sub-processes with a gradual increase of product value and also increasing environmental loads caused by the upgrading processes. When a material or product is recycled into a new product and environmental loads are to be allocated between the two product life cycles, some crucial issues have to be treated:

1) What functions and/or values are recycled in the secondary material R?
2) How accessible is the primary produced material (V) for the following material production (R)?

Concerning issue 1, the virgin material is upgraded in several steps until the final material VF. The question is which of the qualities is recycled into material RG? If, for example, the quality increase from Vn into VF is not reused in the recycled material RG, it can seem fair that only loads from V0 to Vn are allocated forwards. Further, maybe an intermediate, recycled material Rm can be detected which benefits from the production steps V0 into Vn, i.e. that the further production steps from Rm into RG do not benefit from the production steps Vn and onwards. Therefore, only the recycling processes from R0 to Rm should be allocated backwards to the product cycle of P1. Here, the economic values of Vn and Rm can be used to express the quality degradation. Vn and Rm can be seen here as the two intermediate materials, which most fairly constitute a basis for the allocation procedure.

3.3 Design factor

The design factor is a parameter that is used in this method to try to take several characteristics of the assessed material or component and its context on the building level into account. The characteristics that are to be established to be able to determine the design factor for recyclable materials are the permanent loss of material in:

- the primary production process (DF1)
- the building material or component production process (DF2)
- the building construction process (DF3)
- the use of the material or component (DF4)
- the demolition and sorting process (DF5) and
- the secondary material production process (DF6)

Furthermore, an opinion has to be established about the building context into which the building material or component is to be built. This is established in order to be able to determine the possibility of recycling due to geographical location (DF7) and the type of application and the resulting accessibility of the material (DF8).

The factors DF1 - DF6 are material, building material or component specific, and the information can be found on system level 1-3, see Fig. 1, while the factors DF7 and DF8 are to be found on level 4, the whole building as one system. An implication of the fact that information regarding the different factors can be found on different system levels is that it is not always possible to determine all the factors, and not even necessary to be able to establish the design factor for a certain study. If, for instance, a material manufacturer produces material for a future unknown product production (low system level), general values of recyclability can be used, e.g. 90% for aluminium as an average not depending on product type. Another example can be an inventory of a new building (high system level) where the application of the building products is known. If, for instance, copper pipes are caste in a concrete floor slab, the residual value of the copper and the recyclability is still high, but the accessibility very low. The cost for dismantling and sorting will probably exceed the recycled material value, which means that the market value of the built-in copper is negative and thereby too expensive to recycle. The recycle fraction can thereby be expected to be zero.

The resulting design factor is based on an approximation of the resulting possibility of recycling in each specific case and is a factor based on experience when information on the building level is used, see example in **Table 1**. The design factor is an approximation of the recyclable fraction, which is called 'RF' in the equations of this method.

3.4 Estimation of economic values and environmental loads

In the model, several economic values and environmental loads need to be estimated. The allocation factors are to a large extent dependent on the relation between the market value for virgin and recycled materials. When manufacturing a primary product, the market values for all materials and products in the different steps refer to today's value. However, the quality reduction (using principle 3) depends on the price relation between new and recycled product/ materials at the time for the recycling process. This means that the price relation has to be estimated after a time period as long as the expected service life for product P1. For building products with a relatively long service life, these values can be hard to predict. As a best estimate, the price rela-

Table 1: Examples of establishing the design factor, information regarding the steel stud is taken from the study 'Recyclability of Light-gauge Steel Studs' (Anderson and Borg 1997) for factors DF1 – DF6. Information regarding the plasterboard is taken from a study of three building materials (Borg 1997) for factors DF1 – DF6, and from a study of plasterboard recycling for factors DF7 and DF8 (Sigfrid 1995)

Factor	**Light-gauge steel stud**		**Plasterboard**	
	Losses [%] (1)	Design influences [%]	Losses [%] (1)	Design influences [%]
The primary production process (DF1)	4%		0%	
The building material or component production process (DF2)	0%		0%	
The building construction process (DF3)	1%		9%	
The use of the material or component (DF4)	0%		0%	
The demolition and sorting process (DF5)	5%		90%	
The secondary material production process (DF6)	3%		0%	
Total material and product-dependent loss potential	**13%**		**91%**	
The geographical location (DF7)		0% (2)		0% (4)
The type of application and the resulting accessibility of the material (DF8)		0% (3)		100% (5)
Total loss potential	**13%**		**100%**	
Design factor	**0.87** (6)		**0**	

(1) Losses of material relative to the amount in each process
(2) The building is situated in a densely populated area with good access and short transportation distances to waste handling and recycling companies.
(3) The steel studs are used in the construction of an interior wall and easily demolished and sorted
(4) The economically feasible transportation distances for plasterboard waste to recycling are about 200 km and the building is situated in a densely populated area with good access and short transportation distances to waste handling and recycling companies, which means that the material most probably will be transported to recycling
(5) The material is heavily contaminated with several layers of paint and is therefore not suitable for recycling
(6) The design factor is not a summation of the different factors

tion of today can be used. One motivation for this is that the market value of recycled materials/products can be expected to follow the market value of virgin materials/products. On the other hand, the ratio between use of primary and secondary material (the size of fraction RF) can be expected to be sensitive to the price of virgin materials. A relative increase in price for virgin materials can increase the amount of recycling because the recycled material probably will gain a higher market price and a larger cost for recycling can thereby be accepted. However, the relation in market value between virgin and recycled material can be assumed to be the same.

This balance will be disturbed if new technology development results in substitution of common materials and thereby considerably decreases their previous market value. Environmental loads of future recycling processes (when allocating loads from virgin production forwards) as well as environmental loads for historic virgin production (when using recycled material and receiving environmental loads from the past) are sources for uncertainty. This uncertainty can be large when using data for current technology to represent historical data. Another reasoning regarding this issue can be used to justify the use of today's environmental loads and economic values as substitutes for historical and future data, this reasoning is presented below.

In **Fig. 5**, it is shown how the primary (virgin) produced material in year n is recycled after the time period of one service life[1] (symbolised by the continuous arrow). When environmental loads and economic values are then estimated for the recycling process, it should regard the future recycling values at year n+SL. However, using today's values for the recycling process (symbolised with the dotted line), can be motivated if the total amount and mix between secondary and primary material in the recycling pool is constant over time. In that case, it can be seen as a 'load trade' between the producer of products based on primary material and the producer using secondary material during the same time period (year n). The producers using primary materials allocate their loads forward to the material pool for secondary production. The user of the pool accepts today's values for primary production to calculate the loads from the secondary material pool instead of using values for year n-SL (which can be several decades ago for building products). This approach for using today's values gives the benefits that:

1) Environmental loads from history and the future do not need to be estimated. Values of today can be used.
2) The economic values of today can be used to express quality degradation
3) The allocation proposal can be agreed upon today between producers using primary and secondary materials.

The largest drawback is the variation over time in the amount of primary and secondary material production. The variation leads to the fact that a certain amount of material will always be ascribed the values (economic and environmental) from an incorrect point in time.

[1] The service life (SL) in Fig. 5 shall be regarded as an average service life for a product using the analysed material.

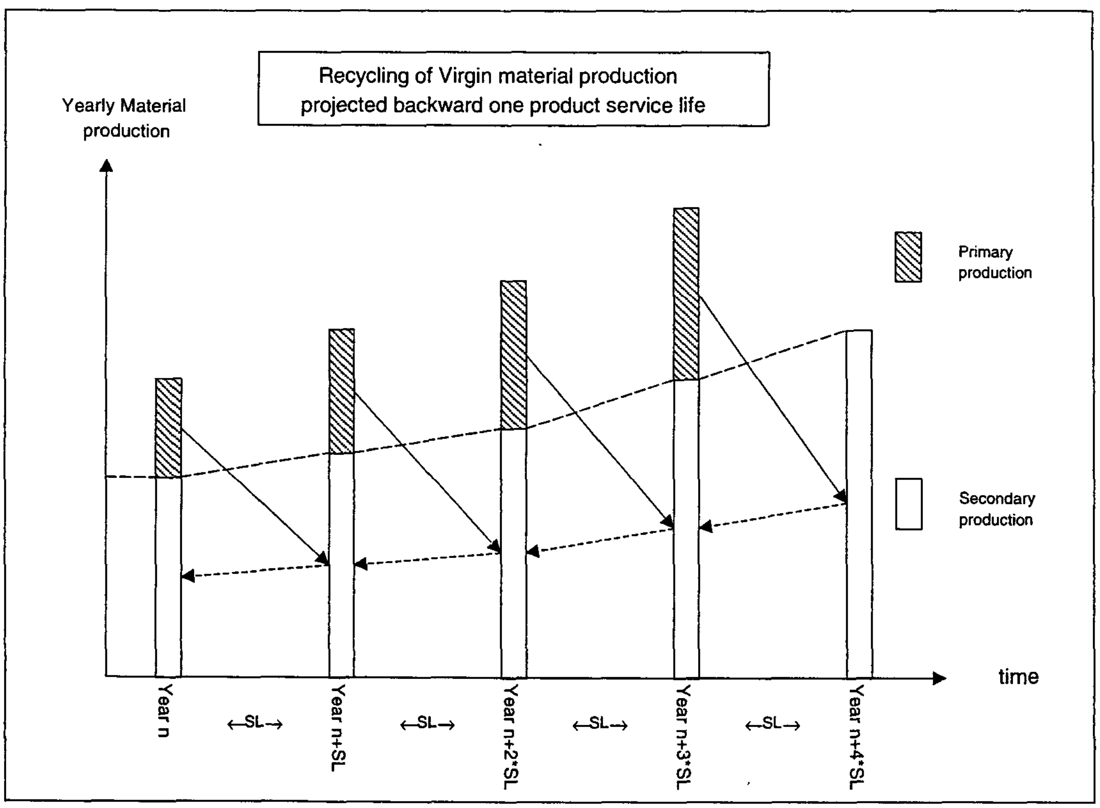

Fig. 5: Principles for back casting the recycling process into today's values

Where to find economic values

Using economic values for allocation demands the existence of these values, and consequently appears only feasible when a market place for recycled materials is established. Examples of data sources for economic values can be such as the LME-index for metals or the finish FOEX-index for pulp based materials. In Sweden, several raw material markets exist, such as the 'Ragnsells' (Ragnsells 2000) homepage, trading with several recycled materials as polymeric materials, rubber, glass, steel scrap, etc., or the 'Bygg igen' database (Bygg igen 2000), trading materials like clay bricks, timber, concrete, sheet materials, etc.

4 Description of the Proposed Method for Recycling of Primary and Secondary Material

4.1 Description of the proposed method for recycling of primary material

In the process model (see Fig. 3), all environmental loads beginning with product V0 and through the production chain to product V_n are called $L_{V0\to Vn}$, $n \in [2,3 \ldots F]$, depending on the number of intermediate products and where F is the final material as an input to product P1. The market value for virgin raw material or intermediate product (Vn) is called S_n. In the recycling process, the starting point is the virgin material (R0) preserved in a product (P1) just before dismantling. Environmental loads from the recycling into R_m contain the steps from material R0 to R_m, here called $L_{R0\to Rm}$. The market value for recycled material R_m is called T_m. During the upgrading process, a material loss can occur (waste fraction WF) and only the fraction RF is available for recycling[2]. The value of n is the number of the intermediate primary material V, which benefits the recycled product R. R_m is the recycled intermediate product, which is comparable to product Vn.

Using the principles 1-3 described earlier, a part of the $L_{V0\to Vn}$ can be allocated forward here called $L_{forward}$:

$$L_{forward} = RF \times L_{V0\to Vn} \times \frac{T_m}{S_n} \tag{1}$$

[2] Material losses will probably occur in several stages between material Vn and Rm so the fraction WF shall be regarded as the total material losses from material Vn into the recycled material Rm, which is the basis for the economic comparison.

However, because of principle 1, the product cycle for the virgin material has to take responsibility for the upgrading of the recycled material from level R1 to R_n, thereby the loads from the recycling processes are allocated backwards to product cycle of the primary production here called $L_{backward}$:

$$L_{backward} = RF \times L_{R0\to Rm} \tag{2}$$

The total environmental loads ascribed to product P1 can be calculated as $L_{productP1}$, see equation (3) and (4), where V_F is the final material as input to product P1.

$$L_{productP1} = L_{V0\to VF} + L_{productionP1} + L_{useP1} + WF \times L_{WasteP1} - L_{forward} + L_{backward} \tag{3}$$

$$L_{productP1} = L_{V0\to VF} + L_{productionP1} + L_{useP1} + L_{useP1} + WF \times L_{WasteP1} - RF \times L_{V0\to Vn} \times \frac{T_m}{S_n} + RF \times L_{R0\to Rm} \tag{4}$$

It should be noticed that this method only promotes recycling if equation (5) is true.

$$L_{V0\to Vn} \times \frac{T_m}{S_n} > L_{R0\to Rm} \tag{5}$$

4.2 Description of the proposed method for recycling of secondary material

The model is additive between the primary and secondary cycles, using values for the same time period (see section about economic values and loads). Recycling of material into a material in a new product which can be recycled further into a new product, results in an exchange of loads (allocation) between the product under study and the previous and following product cycle, see **Fig. 6**.

The product cycle recycling material RA can be considered in two different scenarios. Scenario one is when the value or

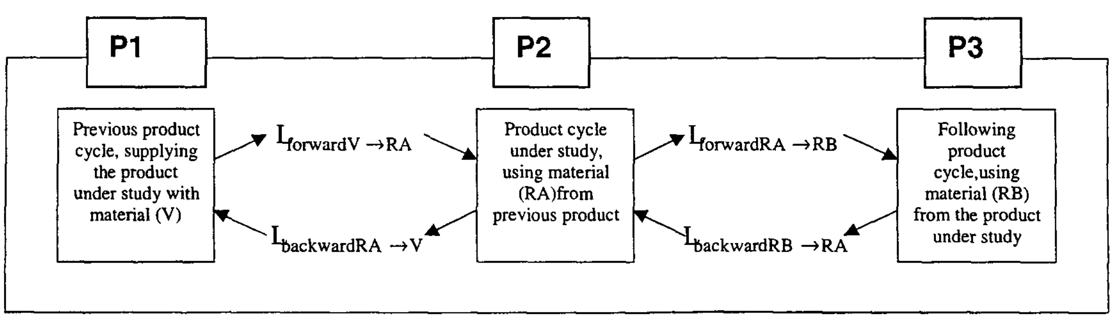

Fig. 6: Illustrating loads to be allocated between different product cycles

quality of material RB is the same as for material RA. Scenario two is when the material RA and RB have different values. Using the suggested model, the product cycle under study has to receive a share of the environmental loads from the preceding product cycle, caused by either virgin production, here called $L_{forward\ V \to RA}$. At the same time, loads from the upgrading and recycling process of material RA can be allocated to the preceding product ($L_{backward\ RA \to V}$), because of principle 1. Following the same arguments, a part of the received load from the virgin production can be allocated forward from material RA to RB, here called $L_{forward\ RA \to RB}$, and at the same time receive

the load $L_{backward\ RB \to RA}$.

$$L_{forwardV \to RA} = L_{V0 \to Vn} \times \frac{T_{m(RA)}}{S_n} \tag{6}$$

Where Tm(RA) is the value of Rm (comparable intermediate product) in the upgrading of RA.

$$L_{backwardRA \to V} = L_{RA0 \to RAm} \tag{7}$$

Meaning that the upgrading process (into intermediate product RAm) is allocated backwards. The part to allocate forward from material RA to RB is based on the fraction RF of RA recycled into RB.

$$L_{forwardRA \to RB} = RF \times L_{V0 \to Vn} \times \frac{T_{m(RB)}}{S_n} \tag{8}$$

Principle 1 can thereby motivate the allocation of the recycling process for RB (into intermediate product RBm), for the fraction RF.

$$L_{backwardRB \to RA} = RF \times L_{RB0 \to RBm} \tag{9}$$

The total loads allocated to the product using material RA are therefore:

$$L_{Allocated \to RA} = L_{forward\ V \to RA} + L_{backward\ RB \to RA} - L_{forward\ RA \to RB} - L_{forward\ RA \to RB} \tag{10}$$

$$L_{Allocated \to RA} = L_{V0 \to Vn} \left(\frac{T_{m(RA)} - RF \times T_{m(RB)}}{S_n} \right) + RF \times L_{RB0 \to RBm} - L_{RA0 \to RAm} \tag{11}$$

Equation (11) is valid for materials (RA and RB) with different values. In the case that the material RA is recycled into material RB with the same quality or value ($T_{m(RB)} = T_{m(RA)}$), and assuming that the impacts from the recycling processes are also the same, equation (11) can be reduced to equation (12):

$$L_{Allocated \to RA} = (1 - RF) \times L_{V0 \to Vn} \times \left(\frac{T_{m(RA)}}{S_n} \right) - (1 - RF) \times L_{RA0 \to RAm} \tag{12}$$

5 Example

To illustrate the suggested allocation method, an example is given below. As shown in Fig. 4, the environmental loads from each production step consist of several parameters, although the energy use is selected as sole parameter to simplify the calculations and increase the perspicuity in the following examples. The chosen values for market values and energy use are solely approximated examples and cannot be used in another context.

This example shows how to allocate loads for primary aluminium for aluminium sheets (P1). It is assumed that the application of the roofing sheet is known (building level) and thereby the recyclable fraction (RF) can be estimated to 90%, based on material properties and design. In Fig. 7, a flow chart illustrates the life cycle of P1 and some of the relevant recycling processes. The values refer to one kg of primary aluminium ingot (V3) and one kg of recycled aluminium ingot (R3).

The recycled material is gained by the primary production from V0 to V3. The process V3→V4 (alloys) does not favour further recycling of the aluminium, it decreases instead the recycle value. However, the alloys are needed for the specific application in product P1. If one could be sure that the aluminium from the roofing sheets was recycled into new roofing sheets requiring the same type and content of alloy, the process V3→V4 could be regarded as gaining the recycled material. With today's knowledge, it is most probable that the material is recycled into an alloy-contaminated pool, not benefiting from the alloys. Most reasonable therefore is to regard material V3 and R3 as most equal to each other. Using the proposed principles, the $L_{forward}$ and $L_{backward}$ can be calculated using equation (1) and (2), see equation (13) and (14). Only the energy use is used as an indicator for environmental loads:

$$L_{forward} = RF \times L_{V0 \to V3} \times \frac{T_3}{S_3} = 0.9 \times (2 + 36 + 84) MJ/kg \times \frac{10.8 SEC}{13.7 SEC} = 86.5 MJ/kg \tag{13}$$

$$L_{backward} = RF \times L_{R0 \to R3} = 0.9 \times (1 + 2 + 10) MJ/kg = 11.7 MJ/kg \tag{14}$$

Thereby, the total amount of energy allocated from P1 into P2 is (86.5-11,7) = 74.8 MJ compared with an actual production energy of 132 MJ/kg for producing alloyed aluminium (V4).

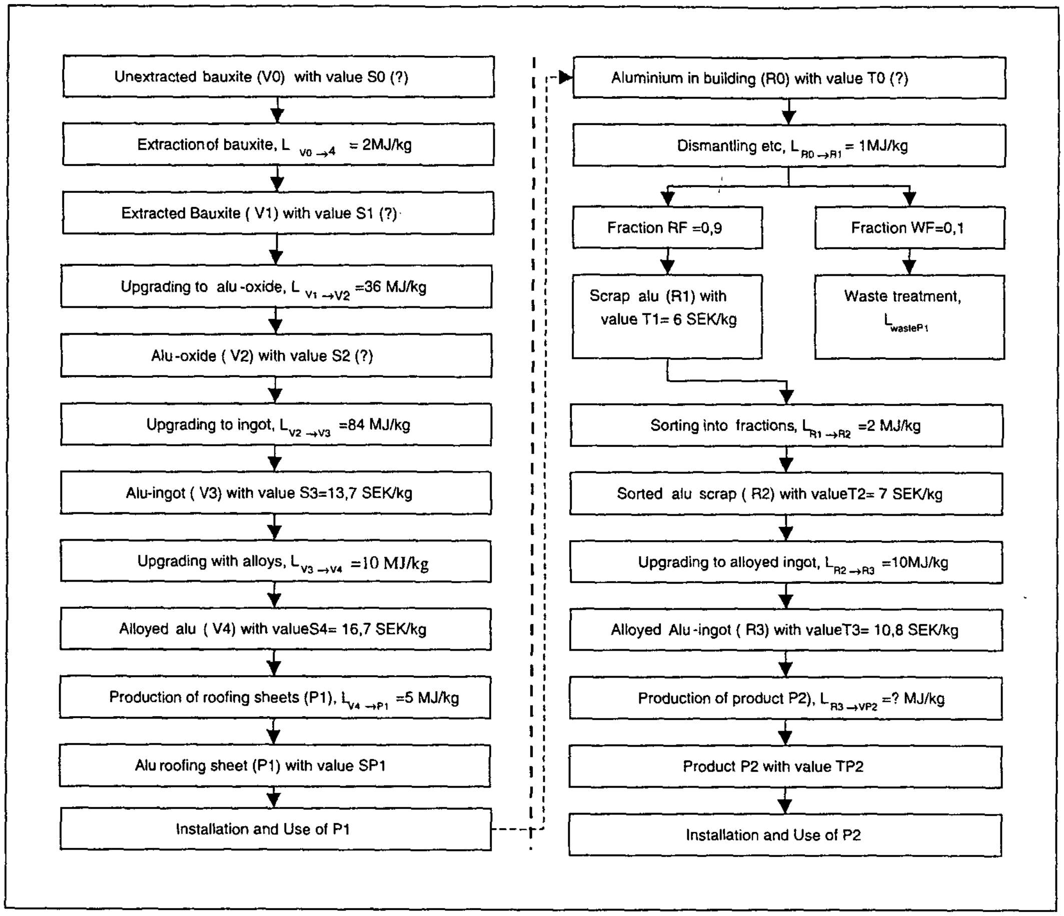

Fig. 7: Production of aluminium roofing sheet, followed by material recycling

6 Discussion

The method presented in this article is based on four fundamental components. These components are: the design factor, the fictive parallel time perspective, the detection of a corresponding intermediate product for which the market value is determined and the use of economic values as an indicator of the remaining quality of recycled materials.

Establishing a design factor is an attempt to incorporate the vast number of factors that affect the potential of recycling in the building sector, in fact both recycling and reuse to some extent, although reuse is not in the scope of this article. The design factor is based on both measurable (DF1–DF6) and experience based factors (DF7 and DF8) to be able to include potential and probable losses of material and obstacles of recycling. The parts of the factors that are measurable are likely to be reproducible, but they will probably vary between different studies. The factors that are experience-based are probably not fully reproducible, as experience of various designs will most likely differ between different executors and experts engaged in the LCA. This problem, however, can be solved, for example, by establishing a generic set of factors for different applications and building materials in the building sector that can be considered acceptable to practitioners in the sector.

The method makes an attempt to handle the problem of the long service lives of buildings and building materials and components by handling the allocation as if the studied production processes occur at the same point in time as the future recycling of the material that is used today. This fictive, parallel time perspective gives us the possibility to handle the large uncertainties that are associated with the prediction of future values and environmental loads of recycled materials, recycling processes and the secondary production of materials that occurs 30 to 100 years into the future. The reasoning behind this is that the distribution between primary and secondary product life cycles and also between two life cycles with secondary material can be negotiated and a consensus can be established based on the participation of the involved parties. A consequence of the fictive parallel time perspective is that we do not have to consider the whole chain of cascade materials, products and activities (Schneider 1994), which enhances the feasibility of the method. Further, the method does at the same time handle the problem of attaining historical values for materials and environmental loads.

The detection of a corresponding, intermediate product for the primary production process (V_n) as well as for the secondary production process (R_m) for which the market value is determined, is of crucial importance to be able to use the

economic value of material as an indicator of the quality after secondary material production. If the values are determined for two not corresponding products, the relations between them will not be an indicator of the quality, as the difference in level of upgrading will distort the relationship.

Several proposals about allocation methods based on material quality have previously been presented, e.g. Hauschild and Wenzel (1998) and Karlsson (1998) and also methods based on economic values like the approaches proposed by Huppes (1994) and Frischknecht (1998). In the method presented, an attempt is made to take the quality and usefulness reduction of materials into account by the use of economic values of materials. The advantage and the disadvantage with the use of economic values as an indicator for the quality compared to use a static degradation factor (or similar) is that the economic value is possible to be established at the time of the assessment, and will therefore provide accurate information at that point in time. Furthermore, the value will give an indication of specific material quality and not just an average material quality or usefulness after recycling. However, it is probably not as hard to predict future values of materials as it is to determine future environmental loads of processes that occur as far into the future as in the case of buildings and building materials. The fictive parallel time perspective described above is an attempt to handle the time-related disadvantage. The use of economic values as an indicator of the remaining quality of the output of the secondary production of materials has also been proposed in a recently publish article (Werner and Richter 2000).

The method is designed for the decision context of two or several decision-makers due to a need for negotiations and consensus about the economic values, the design factor and the consequences of the parallel time perspective. If a consensus is reached, this, in turn, leads to the fact that the user of secondary materials today has to inherit a certain amount of environmental loads from the primary producers of today. The method, however, is not suitable for prospective studies as the method to a great extent works with information and values representing the present state, and does not consider changes in the overall market situation (Ekvall 1999).

7 Conclusions

The presented method for open-loop allocation can be a good alternative for allocation in the case of recycling in the building sector if a consensus for the use of the fictive parallel time perspective and the use of the design factor can be established. This is the case because these two components will enable us to handle the long service lives of buildings, and the specific characteristics of the same building materials and components built in to different context.

The two other essential components in the method should not be as hard to establish a consensus about as the first two. This is so since there already is an acceptance for the use of economic values as a basis for allocation (ISO 1998). Furthermore, a parallel to the consensus of finding the appropriate functional unit as a basis for comparative assertions can be drawn regarding the appropriate intermediate product for which the economic value should be established.

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